Preprint Copy -- Paper will be presented at Waste Management 99 in Early March 1999

DUCRETE^{TM} Shielding Applications in the Yucca Mountain Repository

William J. Quapp
Starmet Corporation
860 W. Riverview Drive
Idaho Falls, ID, 83401

1. ABSTRACT

Present plans for the proposed repository at Yucca Mountain include encapsulation of the spent fuel and high level waste in a high integrity waste package which will be emplaced using remote handling equipment to protect the workers from high radiation exposure. This paper discusses a shielding system that uses depleted uranium concrete as an overpack around the spent fuel waste package and as a low cost substitute waste package for the high level waste canisters. These overpacks reduce the external dose to levels where, combined with repository ventilation, worker access would be relatively unrestricted. The paper describes both the overpacks and estimates the added weight for deployment of such devices. The expected impacts on the repository design are also discussed.

2. INTRODUCTION

The USDOE has over 675,000 MT of depleted uranium hexafluoride (UF_6) from the enrichment process accumulated over the last 50 years. The UF_6 once was conceived as a material for use in the breeder reactor fuel cycle. However, absent a breeder fuel cycle in the foreseeable future, the material has no known use.

In 1993, DOE Environmental Management Office of Science and Technology initiated studies to identify the potential liability associated with disposal of the depleted uranium and to investigate other possible uses. The cost of disposal of UF_6 would include the cost of conversion to an oxide and the subsequent packaging and disposal of the oxide. Depending upon regulations in place and the disposal site, stabilization of the depleted uranium oxide might also be required, thus, further adding to the cost. The net result was an estimated disposal liability that ranged from $3 to $11 billion (Reference 1).

Radiation shielding engineers have used depleted uranium metal in transportation casks where weight or size limits required maximizing the shielding efficiency. However, due to its high cost (raw material and fabrication), depleted uranium metal has never been seriously considered as a shielding material for spent nuclear fuel storage systems. It was recognized that if depleted uranium could be deployed at lower cost, then its use in spent fuel and HLW storage applications might be economically feasible. Subsequently, the INEEL staff[1]developed a new radiation

[1] William Quapp and Paul Lessing are the inventors of DUCRETE. Dr. Lessing is still at INEEL while Mr. Quapp has joined Starmet Corporation.

shielding material where the high atomic weight benefits of depleted uranium can be used in spent fuel and HLW storage systems without incurring all of the cost for conversion to metal. This concept came to be called DUCRETE as in depleted uranium concrete (Reference 2). A US patent for this advanced radiation shielding material was granted in 1998 (Reference 3).

3. DESCRIPTION OF DUCRETE

DUCRETE[2] concrete uses depleted uranium oxide aggregate – DUAGG[2] -- as the large aggregate in a portland cement concrete mixture. The DUAGG ceramic is produced by liquid phase sintering a mixture consisting of 93 weight percent urania (UO_2) with silica and alumina comprising most of the remaining ingredients. The DUAGG composition was developed to make the UO_2 resistant to oxidation and to allow sintering at a comparably low temperature compared to pure UO_2. DUCRETE is then made by combining portland cement with DUAGG and other ingredients to produce very dense DUCRETE concrete. Table 1 describes two representative samples of DUCRETE. Other mixtures using fly ash and silica fume as fine additives are also being investigated.

Table 1. Composition of DUCRETE Samples (Weight Ratio) and Resultant Physical Properties

Major Ingredients	Sample 7	Sample 8
Cement	1	1
DUAGG	9.6	8.18
Fly Ash	0.2	--
Water	.32	0.29
Density (g/cm3)	5.72	5.87
Compressive Strength (MPa)	29.7	30.6
Both Samples contained small quantities of thin metal steel fibers and superplastizer.		

This high density (5.87 g/cm3 versus 2.24 for normal concrete) results in a superior shielding material for spent fuel and high level waste applications where the source radiation is composed of both gamma and neutron flux. Calculations of shielding performance performed at INEEL are compared to other materials in Figure 1 (Reference 4).

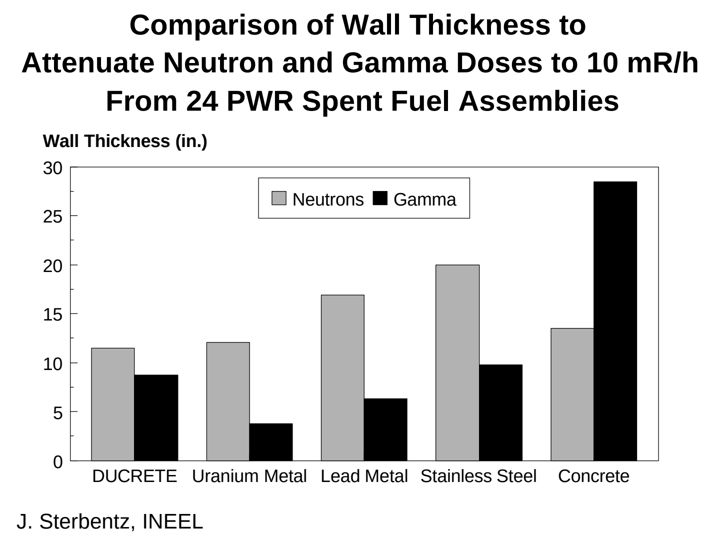

Figure 1 Comparison of Gamma and Neutron Attenuation

Last year, researchers from Japan visited the inventors to discuss their progress in developing depleted uranium concrete (Reference 5). The Japanese investigators have successfully made depleted uranium concrete using depleted uranium oxide pressed UO_2 pellets as the aggregate. Mechanical tests conducted by both investigators have established that the compressive strength properties of the depleted uranium concrete are similar to that of ordinary concrete.

---

[2] DUCRETE and DUAGG are trademarks of Lockheed Martin Idaho Technologies Company

When DUCRETE is used for spent fuel or high-level waste shielding, the casks or overpacks are smaller in diameter and lighter weight compared to casks made from normal concrete. For metal storage casks, very thick walls are required to attenuate both the gamma and neutron source terms unless the metal is combined with another material such as borated polyethylene or concrete.

Several studies were performed by INEEL subcontractors to evaluate the use of DUCRETE concrete in spent fuel storage cask applications (References 6, 7, 8, and 9). An additional, more recent, study was prepared to address a high-level waste storage cask application at the Savannah River Site (Reference 10). Additional evaluations of DUCRETE shielding applications are underway within the Yucca Mountain Project.

4. SPENT FUEL SHIELDING

4.1 Spent Fuel Overpack Design Concept

The design concept for a Yucca Mountain spent fuel overpack is shown in Figure 2. The concept is a right circular cylinder with both bottom and top vents for natural circulation cooling. The vents in this figure are shown schematically and would be designed to minimize shine in the actual overpack. This design concept, similar to several systems available for use at reactor spent fuel storage sites, contains the spent fuel inside of the disposal waste package. The DUCRETE overpack has an interior steel liner and an optional exterior metal shell. The optional exterior shell material could be either carbon steel, stainless steel, or the same C-22 corrosion resistant alloy as used in the current concept of the Yucca Mountain waste package (Reference 11). The use of C-22 would enhance the value of the overpack as a drip shield and provide long-term protection of the waste package, although at a cost increase.

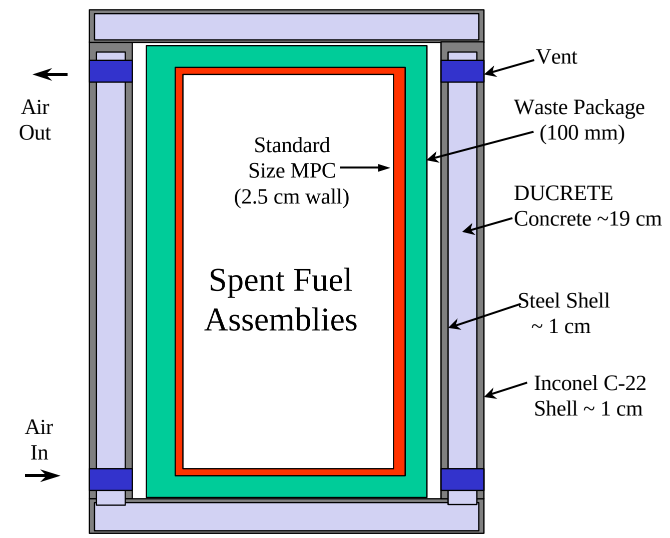

Figure 2. DUCRETE Spent Fuel Overpack Concept

The waste package itself provides considerable radiation attenuation as it is composed of 100 mm of A-516 carbon steel and 20 mm of C-22 alloy. The DUCRETE overpack provides the additional gamma and neutron radiation attenuation necessary to allow human occupancy after the waste packages have been emplaced in a drift. After the waste package is loaded into the DUCRETE overpack, the external dose is reduced to levels safe for contact handling. Additional discussion of the dose reduction is provided in the next section.

4.2 Spent Fuel Radiation Dose Assessment

The potential benefits of a DUCRETE overpack were estimated[3] for a DOE Workshop in 1997 (Reference 12). The average and peak estimated dose from the unshielded waste package is about 8 and 40 R/h. The higher external dose is representative of the burnup from a waste package which meets the 18 kW limiting heat load. Clearly, such a high dose rate eliminates human occupancy in the vicinity of the waste packages. However, with the addition of a relatively thin (19 cm) DUCRETE overpack, doses external to the overpack can be reduced to about 5 and 25 mR/h for the average and peak waste package doses, respectively. The DUCRETE density used in these calculations was 5.24 g/cm^3. No radiation reduction credit was taken for the two 1.27 cm steel shells in this calculation. A 19-cm wall is not necessarily optimum for dose reduction (as higher density DUCRETE has been made) but will be used as the reference concept for the weight calculations in the next section.

4.3 Spent Fuel Overpack Emplacement Weight Calculations

The weight of the DUCRETE overpack and the total waste package system is dependent upon the overpack wall thickness. Thus, there is the balance between external dose to workers and the total system emplacement weight. The weight optimization is beyond the scope of this paper but is dependent upon a detailed evaluation of handling systems in the surface and in the underground facilities combined with ALARA considerations for workers.

For the overpack system described in this paper, the weight of a 19 cm wall DUCRETE package with two 1.27 cm steel shells is approximately 50 metric tons. When combined with the 52 metric ton loaded waste package, the total emplacement weight is about 102 metric tons. Optimizing the composition and taking nuclear credit for the carbon steel and C-22 shells will reduce the total weight by several tons.

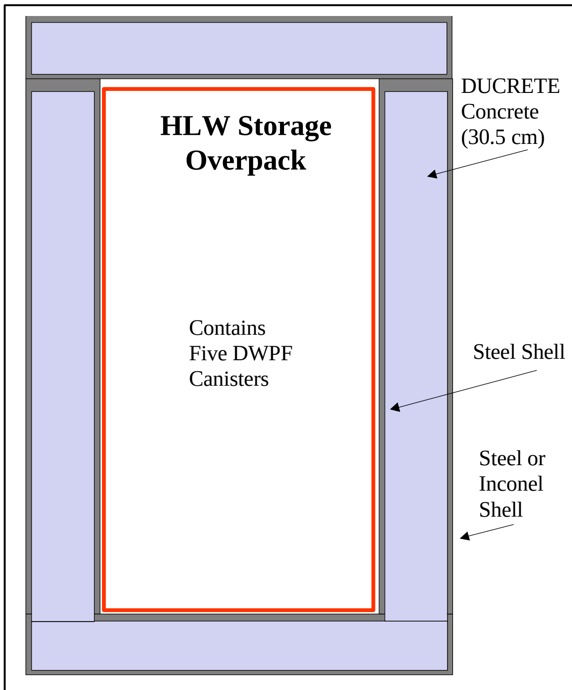

Figure 3. DUCRETE HLW Storage Overpack

5. HIGH LEVEL WASTE OVERPACK

5.1 HLW Overpack Concept Design

The DUCRETE HLW overpack has a somewhat different design concept than for the spent fuel overpack. The concept for the HLW overpack is one that serves two functions – interim storage at the respective DOE site and as a disposal waste package in Yucca Mountain. A conceptual design of the HLW overpack is shown in Figure 3. In this case, the

[3] The shielding calculations were done for the work shop by Dr. Martin Haas of the Yucca Mountain M&O Contractor

overpack is not ventilated. With the relatively thin wall of a DUCRETE overpack and the low thermal energy from HLW glass, the heat can be conducted through the wall of the overpack without causing the HLW glass to exceed its temperature limit of 400°C. A conservative conduction-only-calculation of the temperature profile through the HLW overpack system is provided in Table 2 for bounding values of thermal conductivity and neglecting external convection. The external dose as a function of DUCRETE thickness is shown in Table 3.

This DUCRETE waste package does not have the same long-term durability as the carbon steel and C-22 waste package required for the spent fuel. However, such long-term durability is not needed as the HLW contains minimal long-lived radionuclides and the HLW glass is an inherently a corrosion resistant material.

Table 2. Calculated Overpack Temperature Values for a Range of Thermal Properties

Location	Temperature (°C)	
	Concrete Thermal Properties	Estimated DUCRETE Thermal Properties
Ambient Temperature	38	38
Outer Surface	79	74
Inner DUCRETE Surface	101	86
Inner Carbon Steel Shell	102	87
Average Glass	128	115
Maximum Glass	139	126

Table 3. DUCRETE HLW Storage System Dose Rate as a Function of Wall Thickness

Wall Thickness (cm)	Surface Dose Rate (mR/h)	Dose Rate at @ 2 Meters
25.4	41	10
30.5	19	4
35.6	12	2
40.6	8	1

The high level waste represents less than 2.5% of the curie inventory at the beginning of the repository life and less than 0.02% after 1000 years (Reference 13)[4]. Consequently, considering the low concentration of radioactivity after a few hundred years and the high cost of the spent fuel waste packages, the DUCRETE HLW dual purpose storage and disposal overpack should provide a cost effective alternative to the current carbon steel and C-22 waste package for the HLW canisters.

5.2 Cost Saving From Dual Purpose DUCRETE Overpack

If this DUCRETE dual purpose overpack can be used for both storage at the DOE sites and to replace the Yucca Mountain carbon steel and C-22 waste package for HLW canisters, significant cost savings can be achieved with minimal consequences to long term repository performance.

It has been estimated that 20,000 HLW canisters will be produced from the HLW from SRS, Hanford, West Valley, and INEEL (Reference 14). With 5 canisters per waste package, this equates to about 4000 waste packages. At an estimated capital cost of $350 to $500K per waste

[4] This paper does not address the concepts for incorporation of special nuclear material contained in the HLW canisters or DOE spent fuel located in the same waste package as the HLW canisters. A complete system mass balance and cost optimization needs to be performed to address these issues.

package, replacing the waste package with a dual purpose DUCRETE dry storage system[5] could save in excess of $1.4 to $2 billion of capital cost. Operating cost savings will be additional.

If DUCRETE overpacks are used for HLW storage until Yucca Mountain becomes available, there is no significant incremental cost for the re-use of the overpack in the repository as proposed. The original cost for the DUCRETE overpack for storage is approximately equivalent to a unit cost per canister for free standing storage facility such as the Glass Waste Storage Building used at the Savannah River Site. Due to the small diameter of the DUCRETE overpack, the storage overpacks can be transported empty by rail between the storage site and the Yucca Mountain proposed repository. The HLW canisters will have to be transported in a licensed transportation cask meeting the requirements of 10CFR71.

In addition to cost savings, over the pre-closure period of the repository, a much safer work environment is provided assuring that any unforeseen event requiring human access can be safely accommodated within reasonable means.

6. EMPLACEMENT IN THE REPOSITORY

Several options are available for incorporation of shielded overpacks in the repository. As will be discussed later, one of the major repository design changes necessary to incorporate a DUCRETE shielded overpack for spent fuel is the addition of continuous ventilation. For an overpack similar to that shown in Figure 2, to maintain acceptable fuel temperatures (350°C), an ambient heat sink of about 40°C is required. To achieve this ambient temperature in the drifts, the repository must be ventilated to remove the thermal energy. As discussed in the next section, there are both advantages and disadvantages associated with ventilation but one advantage is that spacing of the disposal packages in no longer limited by the ability of the surrounding rock to absorb the energy. Thus, the repository design could accommodate multiple overpack deployment configurations as shown in Figure 4. Any increases in the cost of the drifts necessitated by this larger disposal package might be offset (at least in part) by the reduction in the length or the number of drifts required.

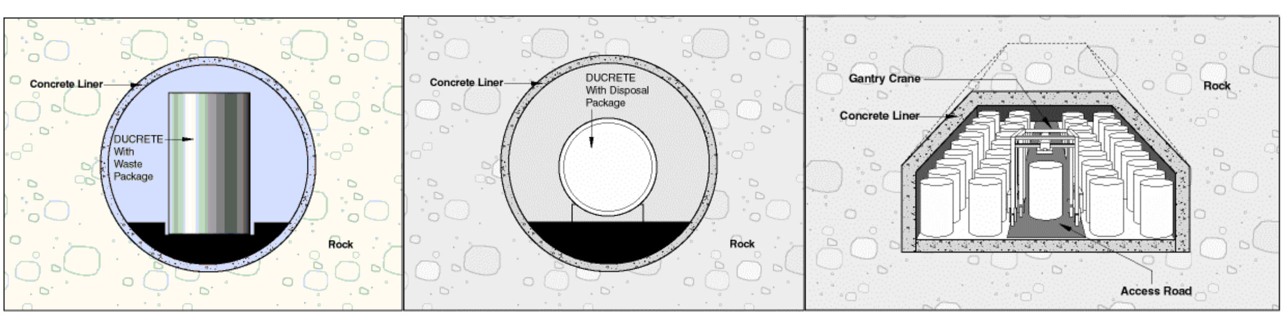

Figure 4. Vertical Emplacement Horizontal Emplacement Alternate Drift Design

[5] Saving projection assumes that the cost of the storage is separate and is a required increment to the above costs. But by using the DUCRETE storage overpack instead of the YM metal waste package for the HLW, then the waste package cost is completely avoided.

All experience with natural circulation cooled spent fuel overpacks similar to that described in this paper is in a vertical orientation. There are virtually no technical issues with a vertical orientation, assuming the proper heat sink temperature is provided. However, in the horizontal orientation, some engineering design challenges such as removable vents will have to be designed and installed. These vents, located in the side of the cylinder, are oriented upward when the overpack is horizontal to allow buoyancy-driven airflow to cool the spent fuel waste package. This concept has not been demonstrated and will require further development to verify its feasibility.

7. EVALUATION OF DUCRETE OVERPACK CONCEPT

The use of a DUCRETE overpacks for spent fuel and HLW canisters as part of the disposal package in Yucca Mountain has certain obvious advantages and disadvantages. A detailed evaluation is beyond the scope of this paper but a qualitative discussion of the major considerations is presented in this section. These assessments are made on the basis of judgement and additional detailed studies are required to validate these opinions. The baseline repository design used for this evaluation is that documented in the Viability Assessment (Reference 11).

7.1 Potential Advantages

The primary advantages of the DUCRETE shielded overpack are the simplification of equipment design for the emplacement of the waste packages and future drift maintenance in Yucca Mountain. The radiation background in the drift would accommodate personnel without requiring extreme measures of protection. Access for repairs in the event of a rock fall or instrumentation failures are comparatively easy in contrast to remotely conducted repairs.

One of the repository requirements for deployment of DUCRETE shielded disposal packages is the addition of ventilation in the drifts. This facility design change complements the radiation attenuation and provides a workspace where operators can have minimal access restrictions. It is assumed that the ventilation system would operate for the entire period that the repository is open. The ventilation system could be forced or natural convection or combinations thereof. Open periods from as little as 50 years to as much as 300 years are being discussed. Clearly at the end of a 300 year operating period, the natural radioactive decay process would reduce the heat load to negligible quantities and subsequent rock heating after closure would be minimal.

Furthermore, a ventilation system will also remove water entering the repository during its pre-closure period, effectively eliminating moisture related corrosion. If the heat is removed via the ventilation air, then, uncertainties regarding the rock behavior from heating to 200°C are also precluded. Durability of the concrete drift liners is also enhanced at low temperature, reducing the probability of drift liner degradation and rock fall during this early period of repository operation. Similar arguments apply to the durability of the concrete inverts below the waste package.

The removal of heat via the ventilation system could allow closer spacing of the waste packages and a substantial reduction of the mined area for disposal package emplacement. This reduction in repository area may also enhance the long-term performance of the repository. If the infiltration rate (liters per square meter of repository ceiling area) is uniform above the waste packages, then a smaller repository footprint also results in a lower total ingress of water. If the radionuclide transport processes are solubility limited (uranium), with a smaller footprint, the integrated flux of radionuclides into the groundwater should be lower because of saturation of radionuclides in a smaller volume of water compared to a system that occupies a much larger area for both intercepting ground water and for transport to the saturated zone below.

The DUCRETE overpack also facilitates recovery of any failed spent fuel waste package. The DUCRETE overpack provides physical protection of the waste package against rock fall and also serves as a drip shield. In addition, the DUCRETE concrete provides substantial quantities of depleted uranium in the vicinity of the waste package, which is postulated to beneficially impact concerns over spent fuel dissolution rates and interactions with groundwater. The uranium in the DUCRETE may contribute to saturating the ground water with uranium, thus, slowing dissolution of the uranium in the spent fuel. Similarly, the availability of depleted uranium may positively benefit postulated re-criticality scenarios.

The repository operating simplification resulting from both the DUCRETE shielded overpacks and the use of ventilation to remove the decay energy may also simplify licensing. The predictability of the repository behavior and the ability to accommodate unforeseen events during the pre-closure period would be improved. With shielded waste packages and a ventilated repository, assuring retrievability of spent fuel or HLW packages present minimal challenges. The elimination of the large thermal pulse associated with heating in the first couple hundred years will also reduce concerns about the rock behavior after the pulse has diminished.

Lastly, this concept provides a synergistic use of the DOE's copious quantities of depleted uranium stored at the enrichment plants in an environmentally responsible manner. Conversion of depleted uranium into DUAGG and DUCRETE reduces the leachability of the material by at least two orders of magnitude compared to direct disposal of U_3O_8 (U_3O_8 is generally produced from the reduction of UF_6). Comparisons of depleted uranium leaching characteristics are shown in Table 4 for DUAGG and several common forms of uranium. Leaching of uranium from DUCRETE would be further reduced because of the encapsulation of DUAGG in the cement matrix.

Table 4. Comparative Leach Test Results for Depleted Uranium Subjected to EPA TCLP Testing.

Uranium Form	Concentration in Leachate (mg-U/liter)
DUAGG	4
UO_2	172
U_3O_8	420
UF_4	7367
UO_3	6900

The UO_3 is from the DOE Savannah River Site and was recovered from reprocessing. The U_3O_8 and DUAGG were manufactured at Starmet CMI from SRS UO_3. The UF_4 was converted from UF_6.

7.2 Potential Disadvantages

Compared to the present repository design, the introduction of the DUCRETE shielded overpacks will require accommodating an emplacement weight of at least 45 to 50 tons more than presently anticipated for the loaded waste package. The ventilation system capacity must be substantially increased to provide sufficient air volume to remove the decay energy and maintain the drift space at approximately 40°C. Alternately, natural circulation might be shown to be effective. The addition of large quantities of depleted uranium on the repository performance assessment must be evaluated. Drift re-design might have to be performed to accommodate changes in disposal package orientation and spacing.

The cost of the overpack for spent fuel will increase the cost of the disposal package. However, total cost impact to DOE (and the taxpayers) may not change much as the country has a responsibility to manage the inventory of uranium hexafluoride (UF_6) in storage at the enrichment plants. If DUCRETE overpacks were used for interim storage at reactor and interim fuel storage sites, no incremental cost would be incurred for use of the overpack at the repository[6]. Both DOE and the utility industry are obligated to pay for the UF_6 management as part of the decommissioning of the enrichment plants (Reference 15). So, integrating the depleted uranium disposal with the spent fuel disposal, should reduce the total system cost to all taxpayers and electricity ratepayers. For the dual-purpose HLW DUCRETE overpacks, a significant net cost reduction is available to offseting cost increases in other areas.

8. URANIUM REQUIREMENTS FOR THE OVERPACKS

Based upon the conceptual design of the overpacks described in Section 4 and 5, the uranium used per overpack is estimated to be 32 and 37 metric tons for spent fuel and HLW, respectively. For a total number of 9,000 spent fuel overpacks and 4000 HLW overpacks in Yucca Mountain, the total uranium consumed for this purpose is about 436,000 metric tons or 651,000 MT of UF_6. This application would consume a large percentage of the total 1998 DOE UF_6 inventory of 675,000 MT.

9. NWTRB RECOMMENDATIONS

The evaluation of simpler alternatives for the repository design has been suggested by the Nuclear Waste Technical Review Board (NWTRB) in their 1996 and 1997 reports to Congress (References 16 and 17). The Board did not specifically suggest the DUCRETE overpack concept, they did suggest that the Yucca Mountain Project consider a ventilated repository design with shielded waste packages. The concept described in this paper complies with those suggestions.

10. CONCLUSIONS

This paper has presented a concept using DUCRETE shielded overpacks for spent fuel and HLW shielding in Yucca Mountain. The concept uses excess depleted uranium from the abundant supplies owned by DOE. There appears to be numerous benefits for design and operation of the repository during the open period with few apparent disadvantages.

The higher density of DUCRETE concrete allows an overpack to be smaller in diameter and lighter weight than a conventional concrete counterpart, thus, offering a unique design option not available before the development of DUCRETE concrete. The overpack conceptual designs

---

[6] However, an overpack suitable for spent fuel shielding at a reactor site when the steel and C-22 waste package is not present, would have to have thicker walls and would weigh considerably more.

described provide sufficient additional gamma and neutron shielding such that the external dose to a worker would be reduced to levels which would allow minimal access restrictions for maintenance or inspections. Thus, worker safety and simplification of future operations is assured.

This shielding application has both positive and negative impacts upon the current repository design concept. The major benefit is the near elimination of remote operations and improved worker safety. Fuel emplacement would now be able to be done without the complexity of a remotely controlled gantry. Recovery from unanticipated events is much more feasible.

The major negative impact upon the repository design is the need to increase the drift ventilation such that heat rejection from the overpacks is sufficient to provide acceptable fuel cladding temperatures within the waste package. However, the increased ventilation has numerous beneficial impacts upon repository design and licensing. The rock temperature and moisture level in the drifts remain at near ambient drift conditions since the heat load and drift moisture are removed with the ventilation air.

Apparent cost savings from the synergy of using HLW storage overpacks replacing the costly metal waste packages helps to offset the increased cost of ventilation. Additional cost savings are accrued from the synergism of solving the DOE UF_6 problem by using most of the depleted uranium tails inventory in DUCRETE overpacks in Yucca Mountain.

Overall, this concept replaces an untested, complex repository design requiring remote operations and maintenance for potentially hundreds of years with one where simplification of operations is achieved using known engineering design principles. DUCRETE shielding enables this shielding concept to be deployed with reasonable weight and size overpacks. These overall advantages are achieved while simultaneously providing a final disposition option for nearly all of DOE's depleted uranium inventory generated from over 50 years of enrichment activity.

11. REFERENCES

1. *Depleted Uranium: A DOE Management Challenge,* USDOE, Office of Science and Technology, Office of Environmental Management, DOE/EM-0262, October 1995.
2. P. A. Lessing, *Development of "DUCRETE"*, INEL-94/0029, March 1995.
3. US Patent No 5,786,611, Radiation Shielding Composition, W. Quapp and P. Lessing, Inventors
4. W. J. Quapp, et al, *Depleted Uranium Hexafluoride: The source material for Advanced Shielding Systems*, Third International Uranium Hexafluoride Conference, November 28- December1, 1995
5. Personal Communication, W. J. Quapp to Koji Shirai, CRIEPI, Research and Development on Depleted Uranium Concrete, December 1997
6. R. T. Haelsig, Packaging Technology Inc., *Depleted Uranium Concrete Container Feasibility Study*, EGG-MS-11400, September 1994.
7. J. E. Hopf, "*Conceptual Design Report for the DUCRETE Spent Fuel Storage Cask System*," INEL-95/0030, February 1995.
8. J. E. Hopf, *Conceptual Design Report for a Transportable DUCRETE Spent Fuel Storage Cask System,* INEL-95/0167, April 1995.
9. F. P. Powell, *Comparative Economics for DUCRETE Spent Fuel Storage Cask Handling, Transportation, and Capital Requirements*, INEL-95/0166, March 1995.
10. Unpublished Report, *DUCRETE HLW Storage System Feasibility Study*, Duke Engineering & Services, Inc., February 1998, Prepared for Starmet Corporation, Barnwell, SC

11. USDOE, *Viability Assessment of a Repository at Yucca Mountain*, DOE/RW-0508, December 1998
12. USDOE, *Proceedings of a Workshop on Uses of Depleted Uranium in Storage, Transportation and Repository Facilities*, Las Vegas, NV, July 15-17, 1997, DOE/EM-0349
13. Nuclear Waste Technical Review Board, Sixth Report to U. S. Congress and the U. S. Secretary of Energy, December 1992
14. USDOE, *Integrated Data Base Report – 1966: U.S. Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics*, DOE/RW-0006, Rev 13
15. USDOE, *Uranium Enrichment Decontamination and Decommissioning Fund*, U.S. Department of Energy, 1998 Report to Congress, Prepared by the DOE Oak Ridge Office
16. Nuclear Waste Technical Review Board: 1996 Findings and Recommendations, Report to the U.S. Congress and the Secretary of Energy
17. Nuclear Waste Technical Review Board: 1997 Findings and Recommendations, Report to the U.S. Congress and the Secretary of Energy